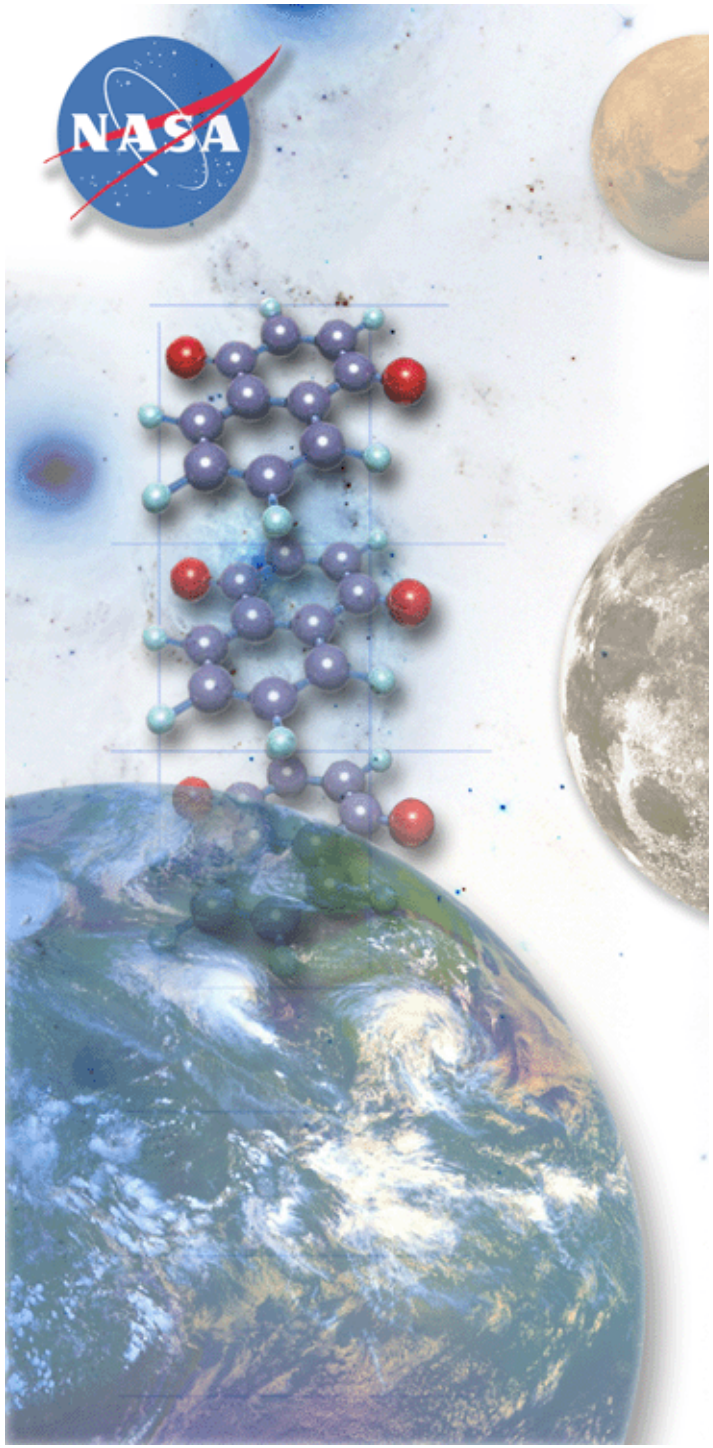
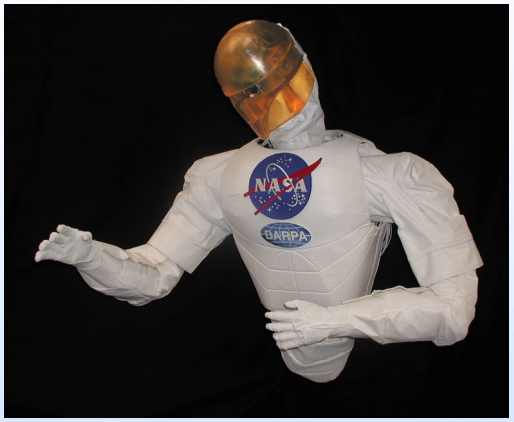


NASA Exploration Team

Final Briefing

May 2002



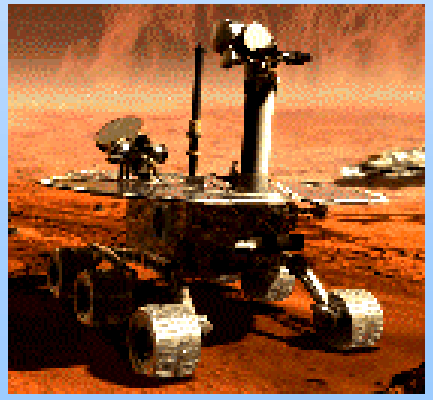
Space Robotic Capabilities

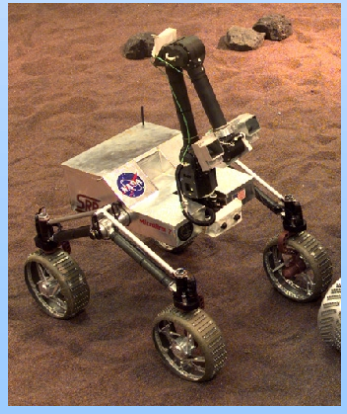
Liam Pedersen (ARC), David Kortenkamp (JSC)

Illah Nourbakhsh (CMU)

David Wettergreen (CMU)

Trey Smith (CMU)

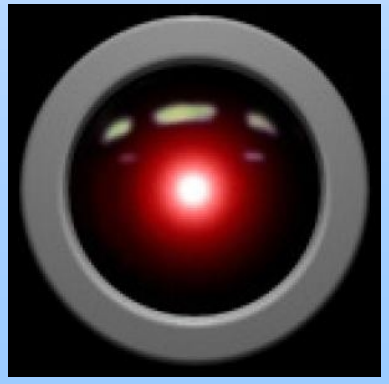




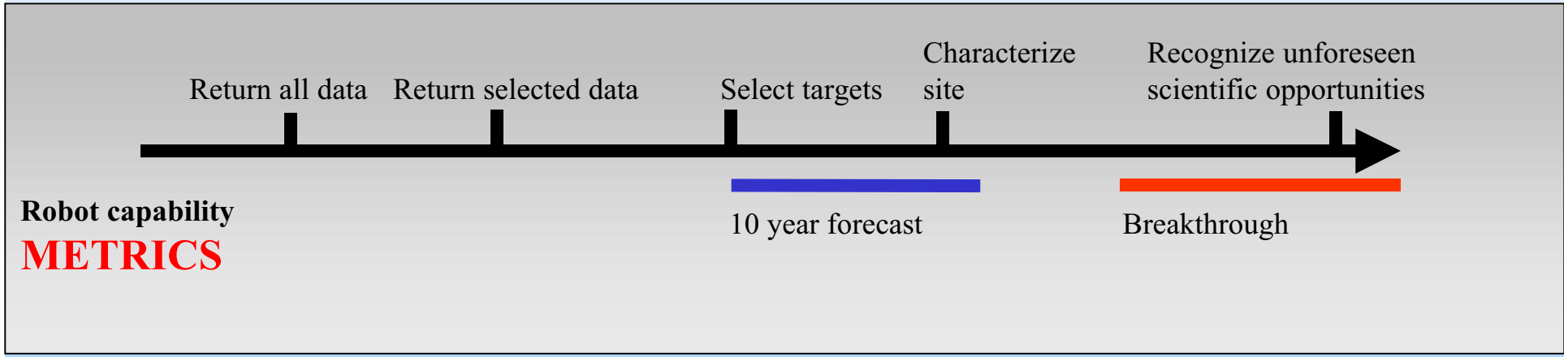
Process and Scope

Introduction

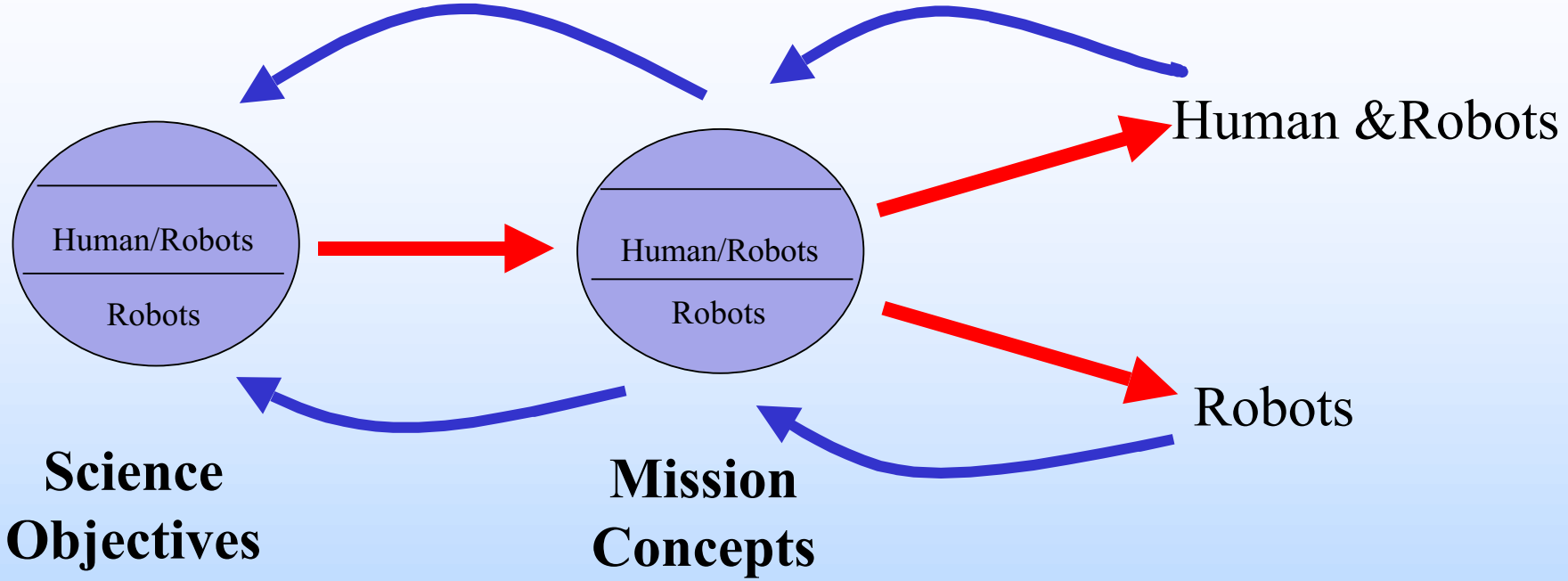
- Need to assess current and future state-of-art of space robotics:
  - Future mission feasibility
  - Technology gaps
- Robots have been used since the beginning of space exploration (c.f. Lunakhod, 1970)
- What limits current robots?
- What does the future hold?

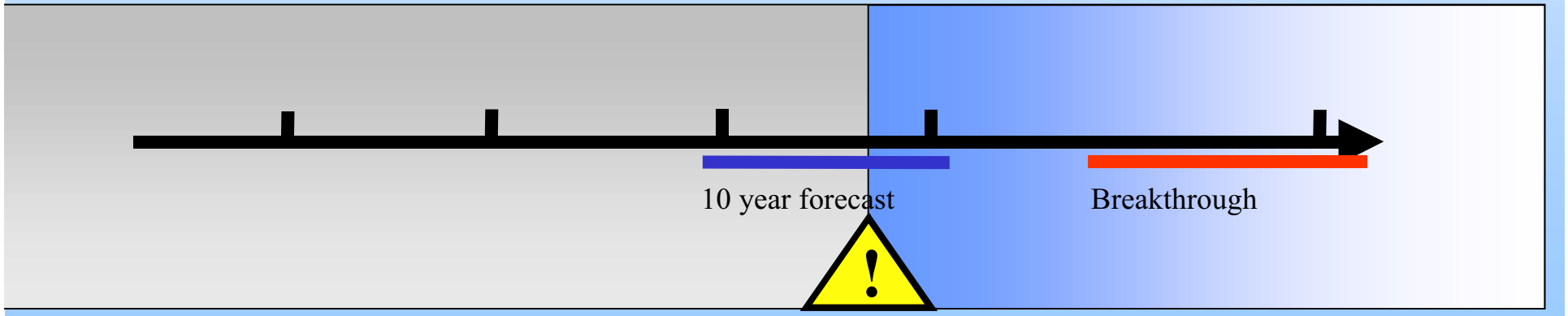


Capability Metrics



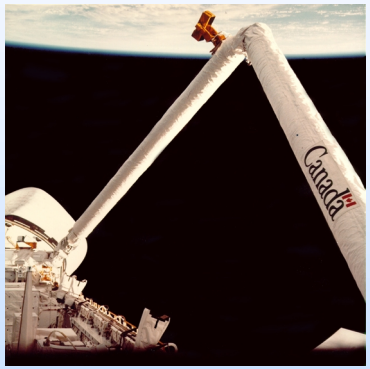
Mission Design Process





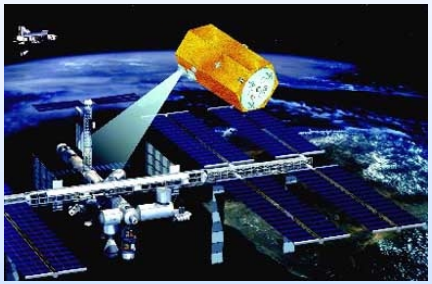
In-Space Functionalities

Assembly



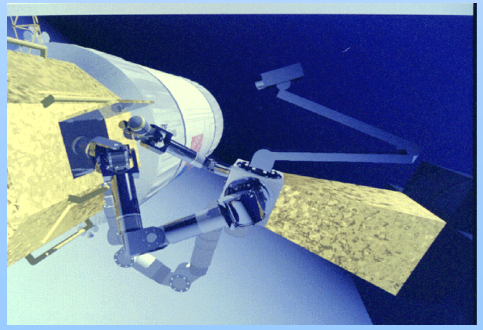
Transporting and mating of components; making connections; assembly sequence planning and execution; assembling small structures

Inspection



Visual inspection of exterior spacecraft surfaces; path planning and coverage planning; automated anomaly detection

Maintenance



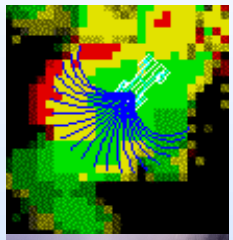
Change-out of components; accessing obstructed components; robotic refueling

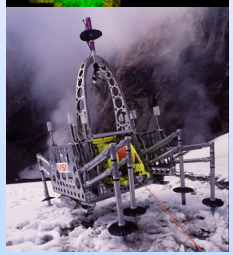
Human EVA Interaction

Monitoring and documenting EVA tasks; preparing a worksite; interacting with astronauts; human-robot teaming

Planetary Surface Exploration Functionalities

Surface Mobility





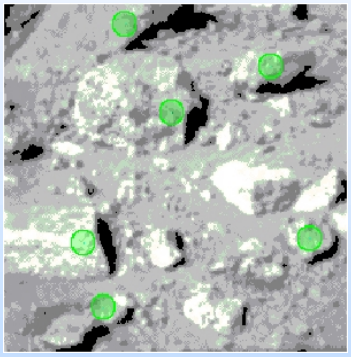
Mobility Autonomy

Terrain assessment, path planning, visual servoing

Mobility Mechanism

Extreme terrain access, energy efficiency

Science Perception, Planning & Execution

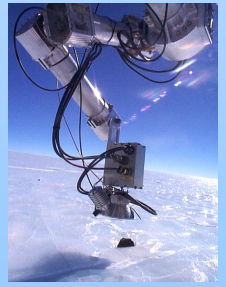


On-board and ground tools; data analysis, target selection, operations planning and execution

Human EVA interaction

Tele-operation to human supervision robot/EVA astronaut teams
Astronaut monitoring and understanding

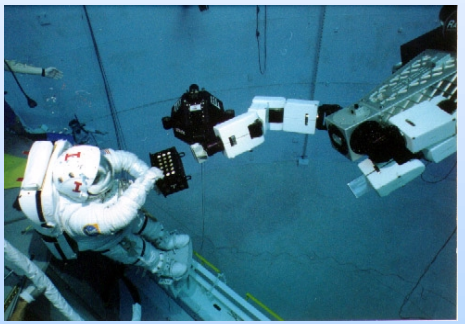
Instrument Placement and Sample Manipulation



Position sensors, collect and process samples

Caveats

- Dangerous to consider humans or robots in isolation. The entire human/robot system must be considered.
- Beware of inaccurate comparisons between human and robotic missions:
  - Massive investment (100's of billions of dollars since Yuri Gagarin) in manned spaceflight:
  - Rigorous training
  - Meticulously choreographed missions
  - Mission Control Center
  - Mercury, Gemini, Soyuz, Apollo, Shuttle, Space Stations.
  - Specialized tools designed for human use.

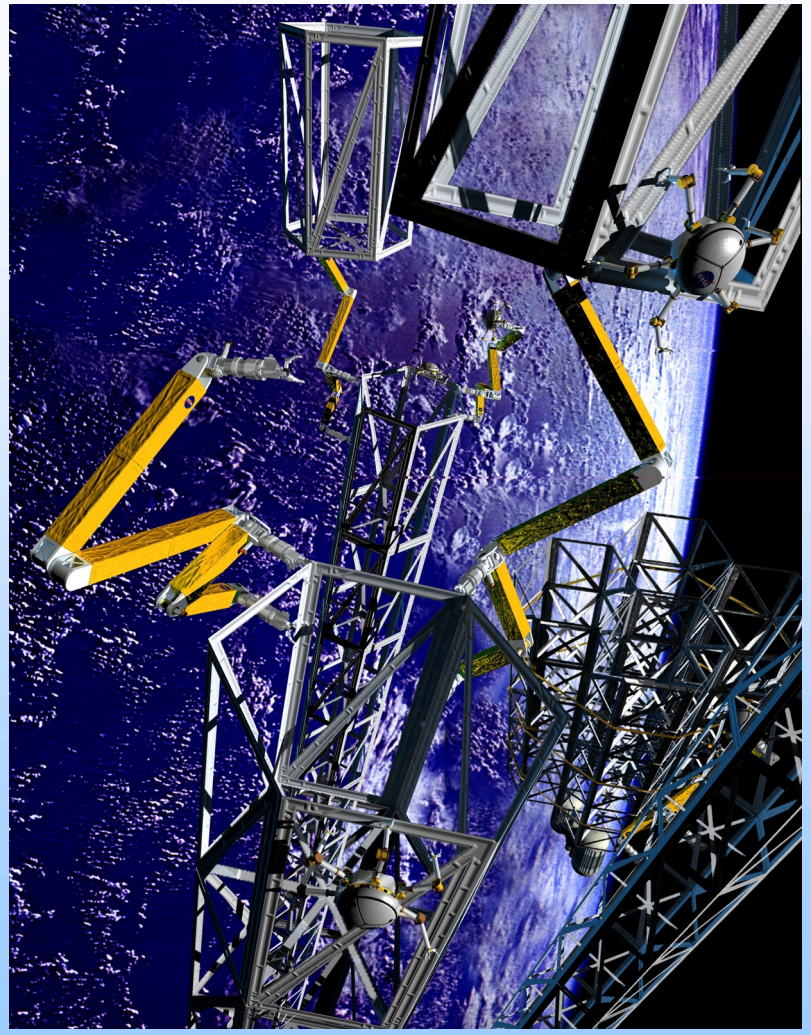


Whole System Design

- Whole system design is essential to success – robots cannot work in isolation:
  - Infrastructure
    - GPS, communications, power,…..
  - Maintenance needs
    - Spares, storage,….
  - **E.g.:** Car factories vs humanoid robots in assembly lines
  - **E.g.:** Langley automated assembly system

Whole system design enables new concepts!

- New concept with non-human robots, self assembling systems



- Human surrogate in a system designed for humans

Sneak Preview of Major Challenges

Programmatic

- System Design
  - "Care and feeding" of robots
  - Infrastructure
  - Interaction with mission designers and user community
- Robustness
  - Sustained testing
  - Diverse technology base

Technical

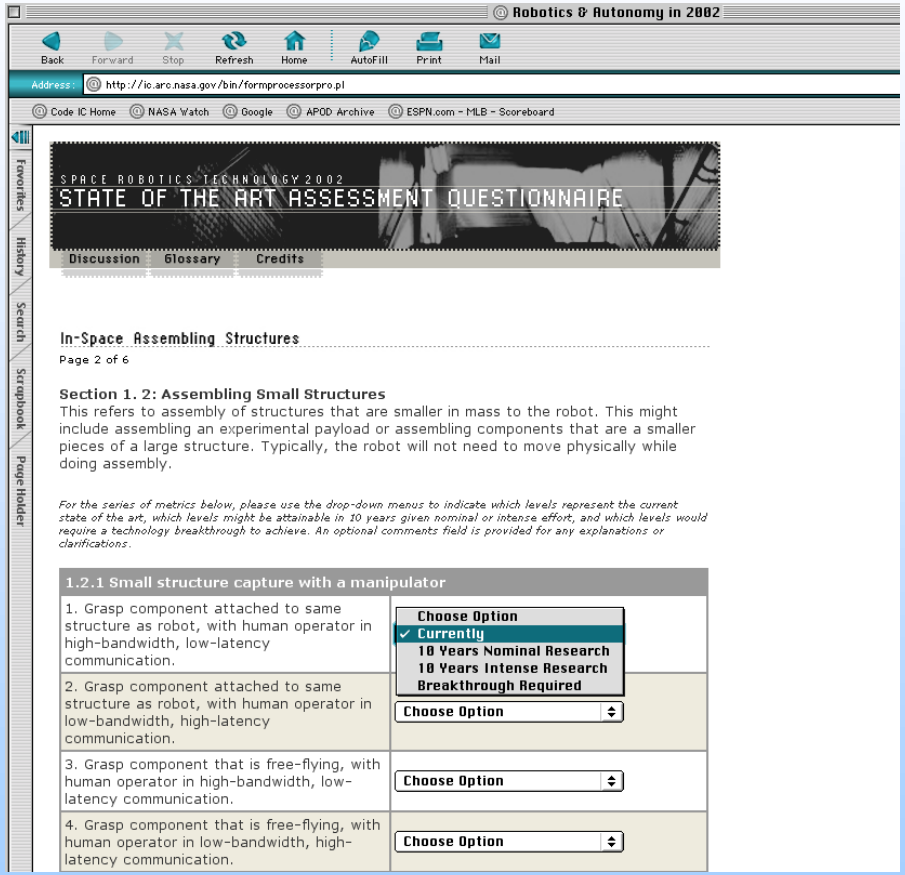
- Robustness
  - Recovery from unplanned situations
  - Health monitoring
- Human-Robot Interaction
  - Virtual presence
  - Teaming
- Mission-Level Objectives
  - AI/Planning
  - Discovery
  - Perception

Site Visits

- **CMU**
  - Red Whittaker
  - Reid Simmons
  - Sanjiv Singh
  - Dimi Apostolopoulos
  - David Wettergreen
  - Takeo Kanade
  - Hans Moravec
  - Sebastian Thrun
  - Peter Staritz
- **Stanford ARL**
  - Steve Rock
- **JSC**
  - Robert Ambrose
  - Robert Burridge
  - Chris Lovchik
  - Robert Savely
  - Jen Rochlis
  - Kim Shillcutt
  - Chris Culbert
  - Kevin Watson
- **JPL**
  - Paul Schenker
  - Paolo Pirjanian
  - Terry Huntsberger
  - Charles Weisbin & Guillermo Rodriguez
  - Brian Wilcox
  - Issa Nesnas
  - Rick Welsch
- **NASA HQ**
  - Dave Lavery
  - Joe Parrish
- **GSFC**
  - Rud Moe
  - William Doggett (Langley)
- **NRL**
  - Alan Schultz
- **ARC**
  - John Bresina
  - Larry Edwards
  - Rich Washington
  - Dan Clancy
- **McGill University**
  - Martin Buehler

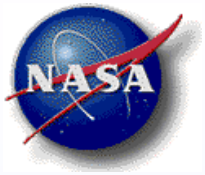
Website Questionnaire

- Questionnaire collected feedback from robotics community on the current state of the art and expected developments in space robotics
- Survey of fielded systems collected demonstrated performance details from existing robotic systems
- Respondents were asked to indicate
  - the **current** state of the art
  - where it might be in 10 years given **nominal** or **intense effort**,
  - where technology **breakthrough** would be required



Survey Respondents

- Carnegie Mellon:
  Matt Mason, Sanjiv Singh, Reid Simmons, Tucker Balch, Devin Balkom, Ben Shamah, Peter Staritz, Illah Nourbakhsh, David Wettergreen, Terry Fong
- JPL
  Rich Volpe, Samad Hayati, Jack Jones, Chris Leger, Issa Nesnas, Brian Wilcox
- JSC
  Steve Frederickson, Chris Culbert, Kimberly Shillcutt, David Kortenkamp, Robert Burridge, Ron Diftler
- ARC
  John Bresina, Rich Washington, Lawrence Edwards, Kanna Rajan, Liam Pedersen
- NRL
  Alan Schultz
- GSFC
  Rud Moe
- LaRC
  William Doggett
- McGill
  Martin Buehler
- UMD
  Dave Akin, Ella Atkins

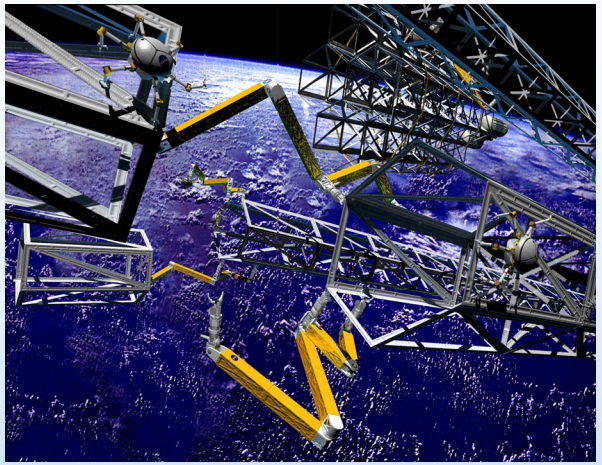


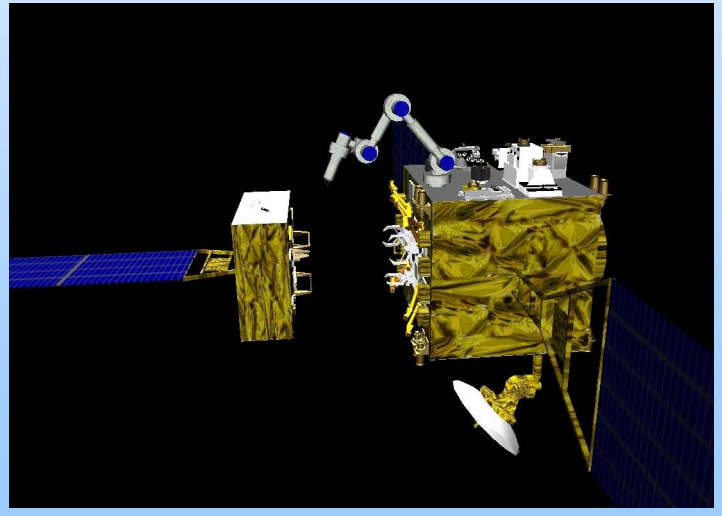
Detailed Assessment of Functionalities

In Space Assembly

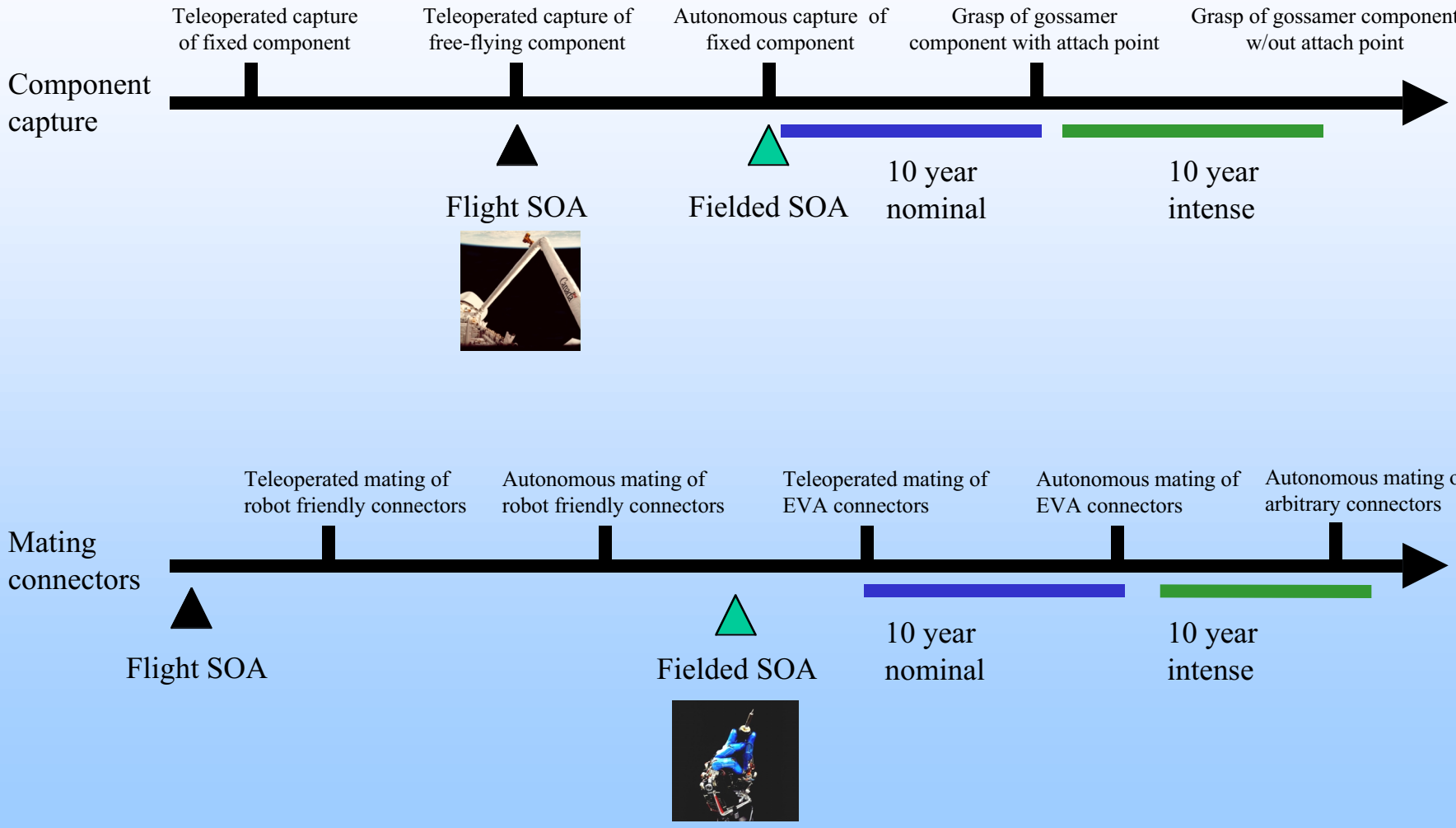
In-Space Robotic Assembly

- **Solved (or will be soon):**
  - Autonomous assembly of carefully designed mechanism in a static, known environment
  - Autonomous mating of robot-friendly connectors
- **Intense effort**:
  - Recovering from errors/perturbations
  - Design and control of high DOF robot systems
  - Manipulation of fragile components
- **Breakthrough**
  - Autonomous assembly planning including responding to unforeseen situations

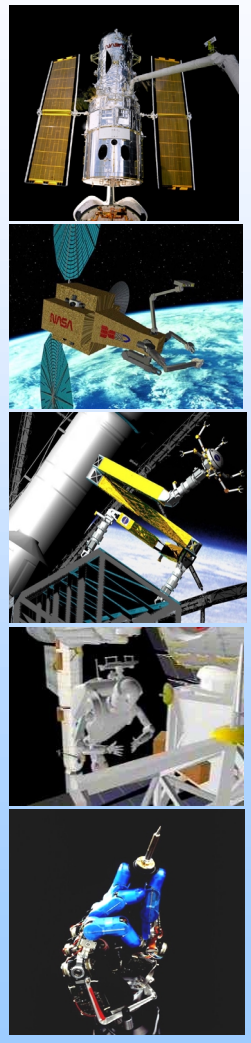




In-Space Robotic Assembly



In-Space Assembly Overall Evaluation



Teleoperated robots that move large components and mate parts

Closely supervised, semi-autonomous robots that move large components and mate parts

Teleoperated robots that can mate parts and make fine connections between parts

Closely supervised, semi-autonomous robots that mate parts and make fine connections between parts

Autonomous robots that move large components and mate parts with minimal human intervention

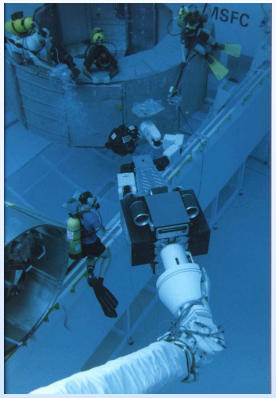
Autonomous robots that mate parts and make fine connections between parts with minimal human intervention

Autonomous robots that perform complete assembly of complicated structure (e.g., large telescope) from start to finish with substantial support from ground-based or in-space humans

Autonomous robots that perform complete assembly of complicated structures (e.g., large telescope) from start to finish with minimal human intervention

In-Space Assembly Relevant Systems

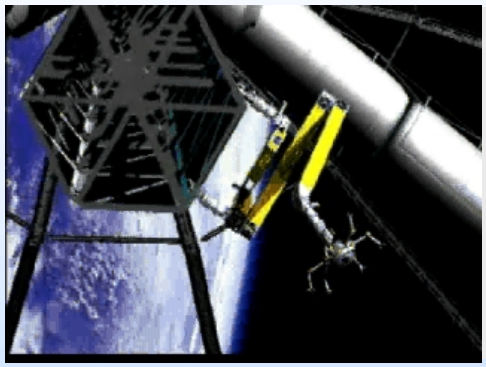
Ranger



Tested in neutral bouyancy facility

Tele-operated

Skyworker

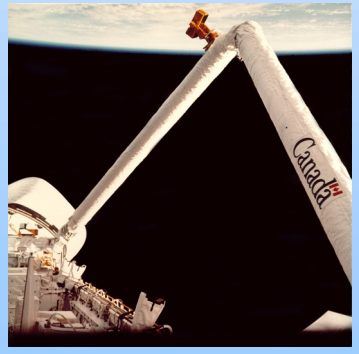


Transport of objects

Motion planning

Low-energy climb on structure

Space Station RMS



Tele-operated crane

Requires special connectors

Limited mobility

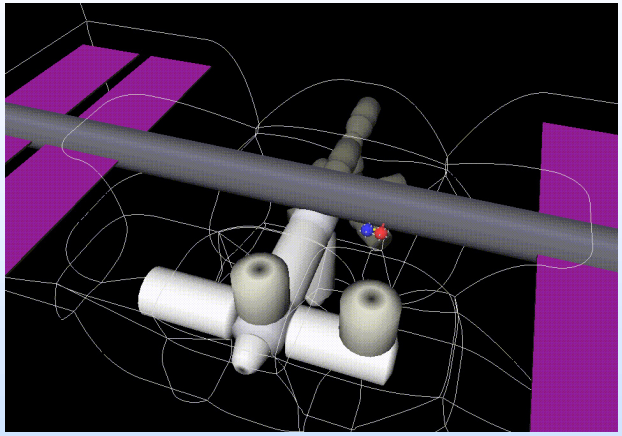
Other Systems

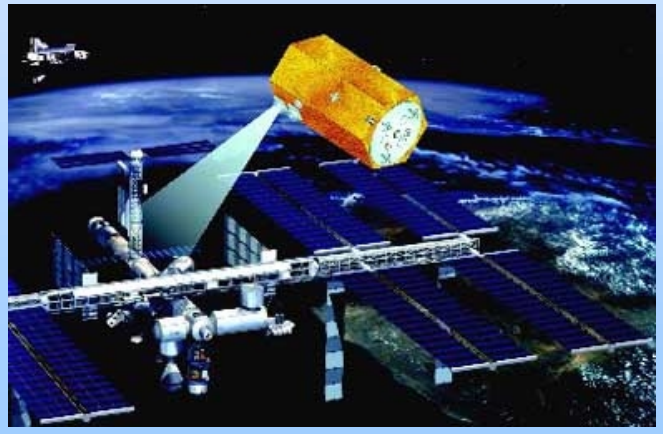
- Robonaut
- Langley Assembly Robot
- ETS-VII
- ROTEX
- ERA
- JEM Fine Arm
- SPDM

In Space Inspection

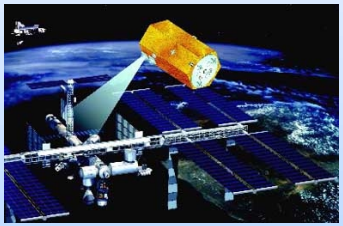
In-Space Robotic Inspection

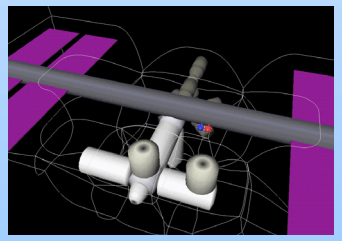
- **Solved (or will be soon):**
  - Mobility and coverage of the exterior of complex structures
  - Autonomous refueling/recharging of inspection robot
- **Intense Effort:**
  - Accessing interior spaces (perhaps using “snake” or other high DOF robots)
- **Breakthrough**
  - Autonomous anomaly detection





In-Space Inspection Overall Evaluation





Robotic visual inspection of some exterior surfaces with no interpretation of sensory data; teleoperated

Robotic visual inspection of some exterior surfaces with no interpretation of data; human operator closely supervising via high-bandwidth communication

Robotic visual inspection of some exterior surfaces; sensory data filtered before being stored or sent; supervised autonomous operation

Robotic visual inspection of most exterior surfaces; autonomous interpretation of most data; supervised autonomous operation

Robotic visual inspection of most exterior surfaces; autonomous interpretation of most data; autonomous refueling and recharging

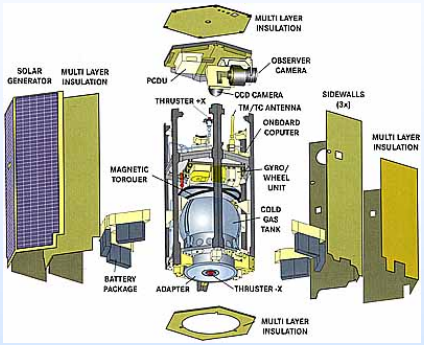
In-Space Inspection Relevant Systems

AERCam Sprint

Teleoperated free-flying camera

Flown on space shuttle

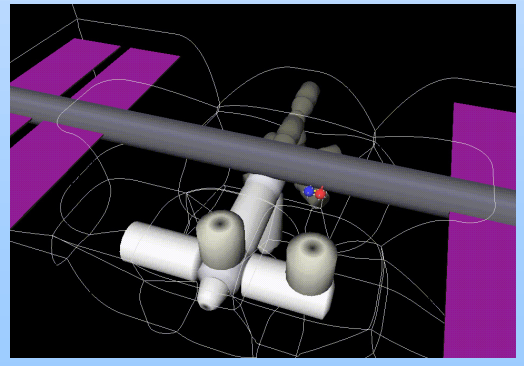
Inspector



Failed in space experiment

Designed for autonomous and teleoperated operation

AERCam IGD and AVIS



Autonomous inspection

Path planning and coverage

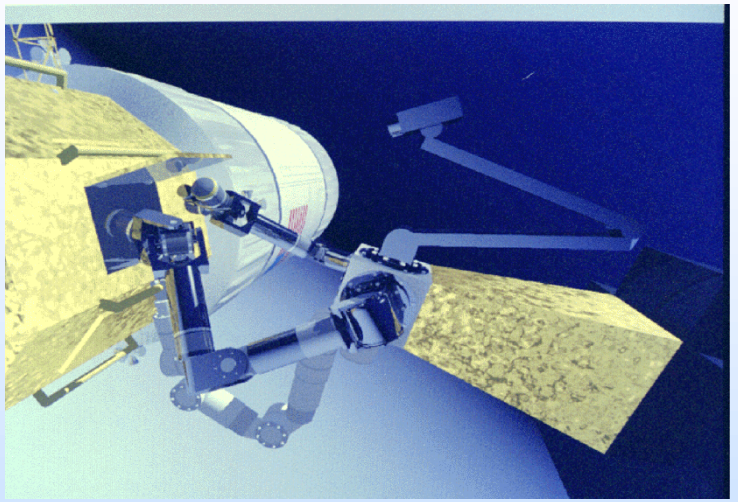
Other Systems

- Charlotte
- PSA (IVA robot)

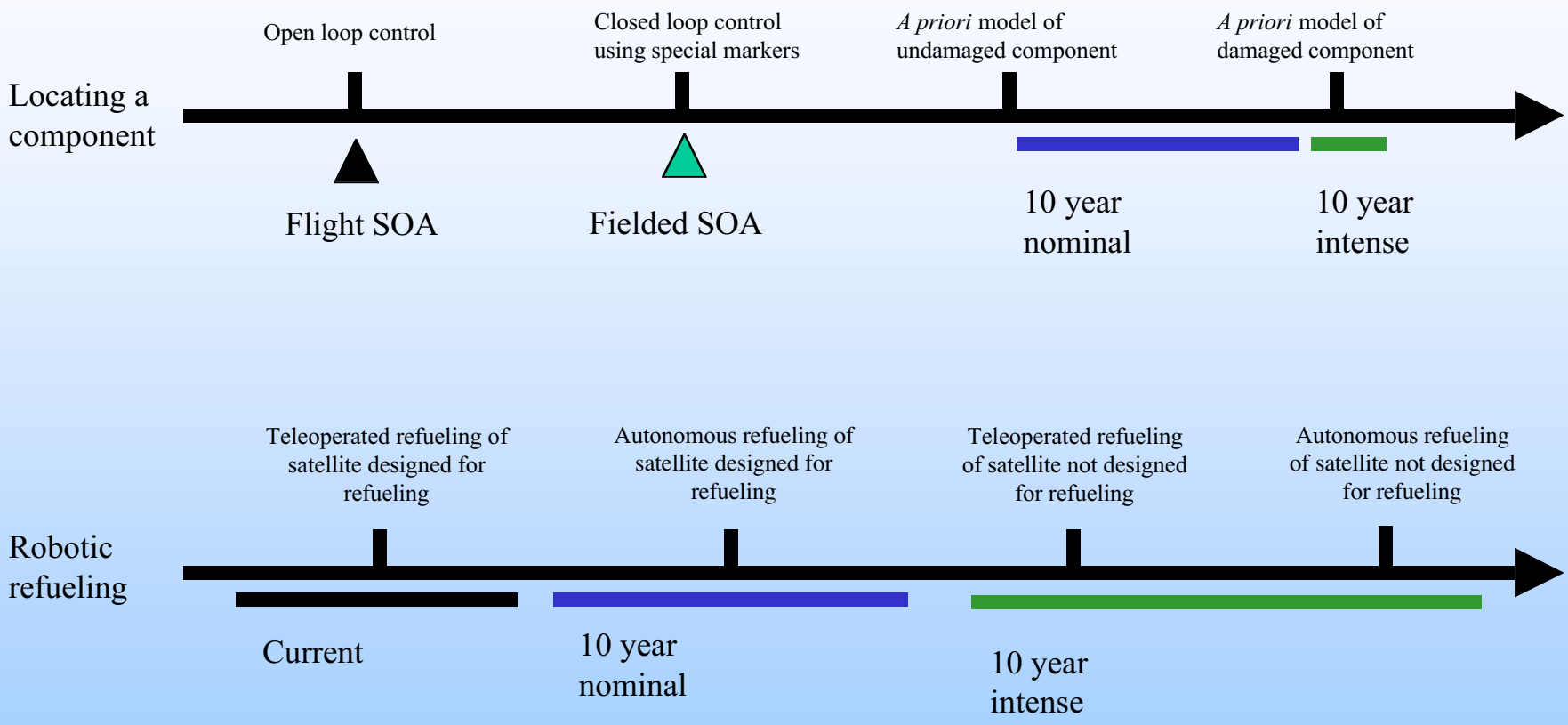
In Space Maintenance

In-Space Robotic Maintenance

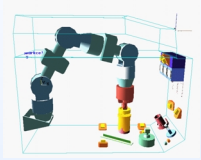
- **Solved (or will be soon):**
  - Autonomous change-out of components that are designed for replacement
  - Accessing components behind covers, blankets, etc. under teleoperation
- **Intense Effort:**
  - Autonomous change-out of components not designed to be replaced
  - Accessing components behind covers, blankets, etc. under supervised autonomy
  - Interaction with badly damaged components
- **Breakthrough**
  - Advanced troubleshooting

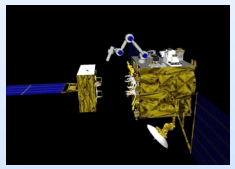


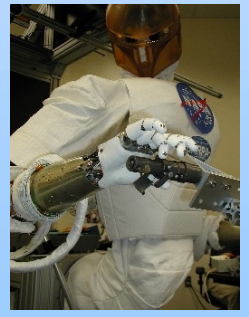
In-Space Robotic Maintenance



In-Space Maintenance Overall Evaluation







Robotic change-out of pre-designed components (e.g., ORUs) under teleoperated control

Robotic change-out of pre-designed components (e.g., ORUs) under supervised autonomous control

Robotic refueling of spacecraft/satellites under teleoperated control

Robotic refueling of spacecraft/satellites under supervised autonomous control

Robotic change-out of arbitrary exposed components under teleoperated control

Robotic change-out of arbitrary exposed components under supervised autonomous control

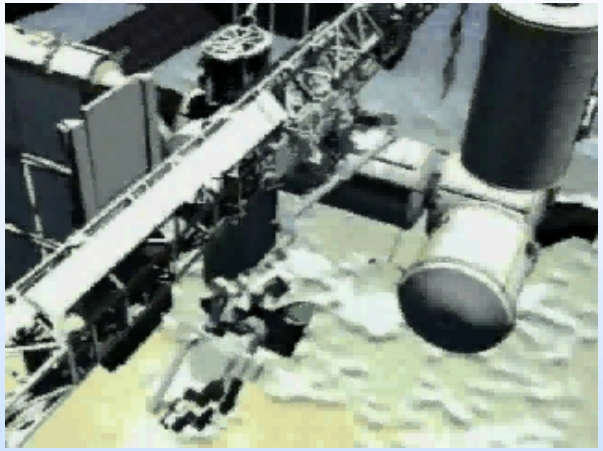
Robotic access to and change-out of arbitrary, obstructed components under teleoperated control

Robotic access to and change-out of arbitrary, obstructed components under supervised autonomous control

Robotic troubleshooting of anomalies and arbitrary repair under supervised autonomous control

In-Space Maintenance Relevant Systems

Robonaut

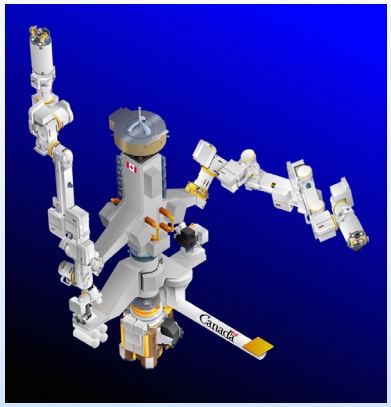


High DOF grippers

Compliant grip

Telepresence interface

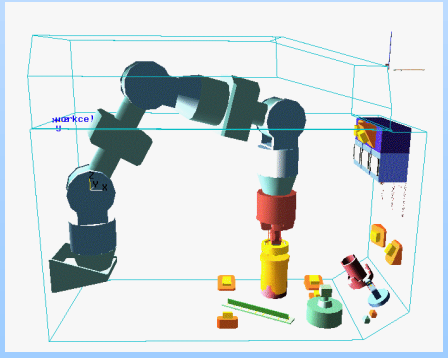
SPDM



Attaches to end of RMS

Multi-arm dexterous manipulation system

ROTEX



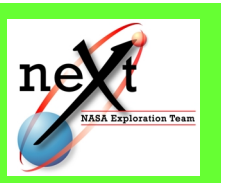
Flown on space shuttle

Performed simple assembly and change-out

Mostly teleoperated, but with some autonomous tests

Other Systems

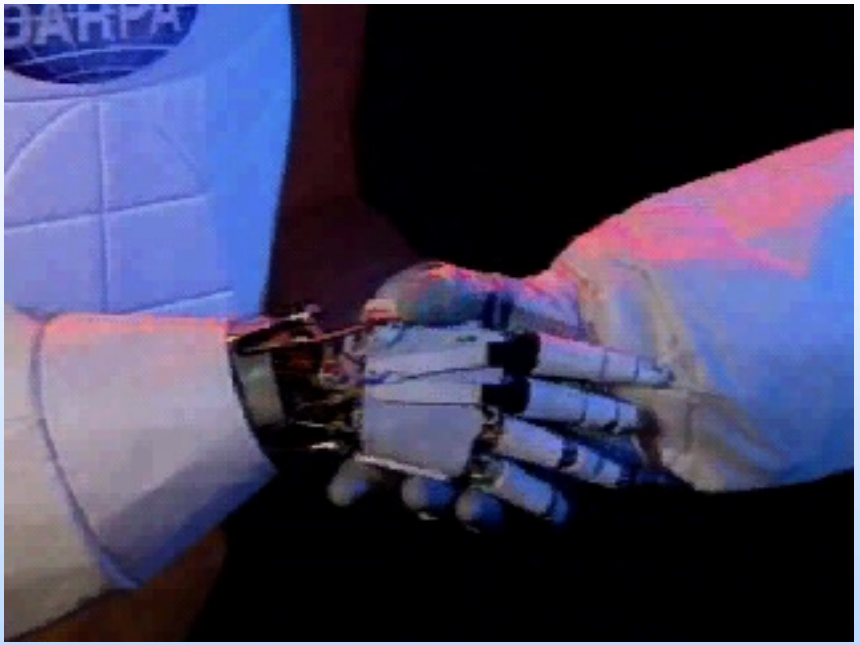
- Skyworker
- ETS-VII
- Ranger
- Progress re-supply vessels



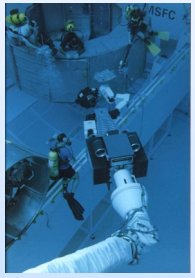
In Space EVA assistance

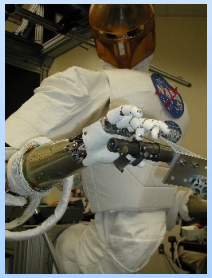
In-Space EVA Assistance

- **Solved (or will be soon):**
  - Tracking of EVA astronauts
  - Physical interaction with astronaut by holding/handing tools
  - Recognition of gestures and natural language commands
  - Site preparation given specific requirements
- **Intense Effort:**
  - Site preparation based on task
- **Breakthrough**
  - Free-flowing dialog between robot and human
  - Recognition of human emotional and physical condition



EVA Assistance Overall Evaluation

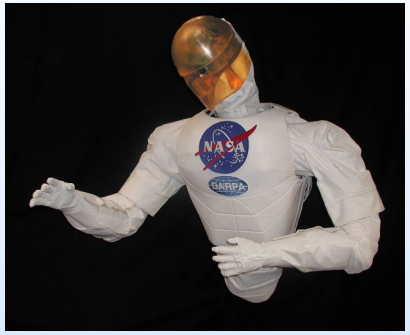




- Robots move humans from one work site to another; human operator in high-bandwidth, low-latency communication
- Robots move humans from one work site to another; human operator in low-bandwidth, high-latency communication with robot.
- Robots do site preparation and cleanup for EVA; human operator in high-bandwidth, low-latency communication with robot.
- Robots do site preparation and cleanup for EVA; human operator in low-bandwidth, high-latency communication
- Robots in same proximity as humans working same tasks but no physical interaction; human operator in high-bandwidth, low-latency communication with robot
- Robots in same proximity as humans working same tasks but no physical interaction; human operator in low-bandwidth, high-latency communication with robot
- Robots that physically interact with humans; human operator in high-bandwidth, low-latency communication with robot
- Robots that physically interact with humans; human operator in low-bandwidth, high-latency communication with robot
- Robots that are true teammates with humans, working on same tasks, responding to natural language, gestures and high-level goals and recognizing human intentions
- Synergistic relationship between human and machine with direct, physical connections and prostheses, i.e., “super” humans augmented with machines

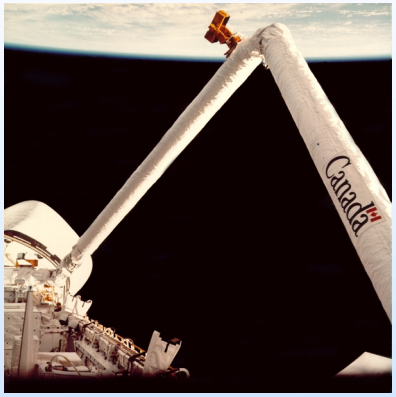
In-Space Assistance Relevant Systems

Robonaut



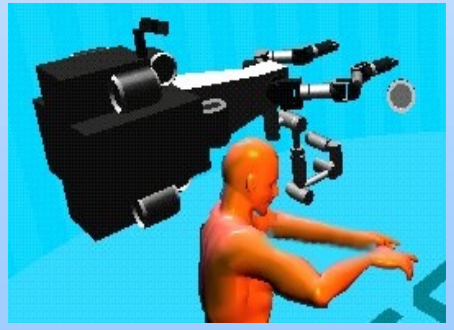
- High DOF grippers
- Compliant grip
- Telepresence interface

RMS



- Teleoperated crane
- Can move EVA astronauts around

Ranger



- Teleoperated
- Tested in Neutral Boyancy Facility

Other Systems

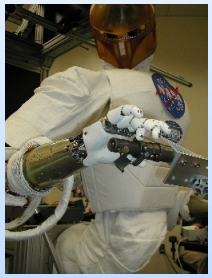
- FTS

Surface EVA assistance

Surface EVA Assistance

- **Solved (or will be):**
  - Following of human (e.g., "pack mule")
  - Site reconnaissance and mapping
  - Gesture recognition
  - Plan recognition
- **Intense Effort:**
  - Site clean-up (e.g., picking up tools, setting up experiments)
- **Breakthrough**
  - Dialog with human crew
  - Recognition of human mental and physical state

EVA Assistance Overall Evaluation



Robot tracks an EVA crew member while carrying tools and a camera

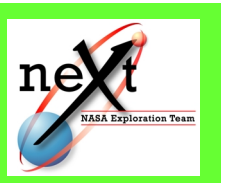
Robots do site survey and preparation as well as post-EVA documentation

Robots carry tools, which they hand to the EVA crew member. Robots can also collect designated samples

Robots physically interact with humans via high-level voice commands and gestures

Robots that are true teammates with humans, working on same tasks, responding to natural language, gestures and high-level goals and recognizing human intentions

Synergistic relationship between human and machine with direct, physical connections and prostheses, i.e., “super” humans augmented with machines



Surface Mobility

Planetary Surface Mobility

Solved (or will be soon):

- Localization and local mapping
- 100's of meters between command cycles
- Coverage patterns
- Visual servoing
- Obstacle avoidance

Intense Effort:

- Most terrain types with specialized machines
- Globally consistent mapping.
- Robust navigation w/o GPS

Breakthrough:

- Single vehicle that can access all terrain types, cover long distances, survive 1000 days AND carry a payload….
- Robust self righting mechanisms.

Surface Traverse Distance

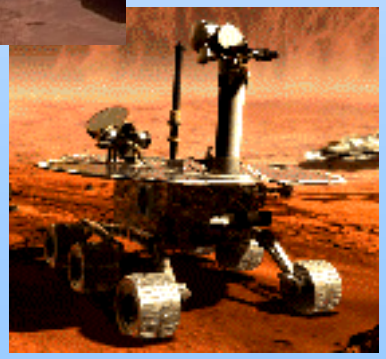
Traverse distance per command cycle

1 m | 10 m | 100 m | 1000+ m

Flight SOA

Fielded SOA

10 year Forecast



Surface Mobility Relevant Systems

Hyperion

- Health monitoring
- Long traverses
- Path planning

Sample-Return Rover (SRR)

- Mechanical reconfiguration
- Model-registration localization
- Rendezvous with lander

Dante II

- Extreme slope access
- Gait planning

Other Systems

- Sojourner
- MER 2003
- Rocky 7/8
- Nomad
- Mars Autonomy Project
- Urban Reconnaissance Robot
- And more…

Surface Instrument Deployment and Sample Manipulation

Surface Instrument Deployment and Sample Manipulation

Solved (or will be soon):

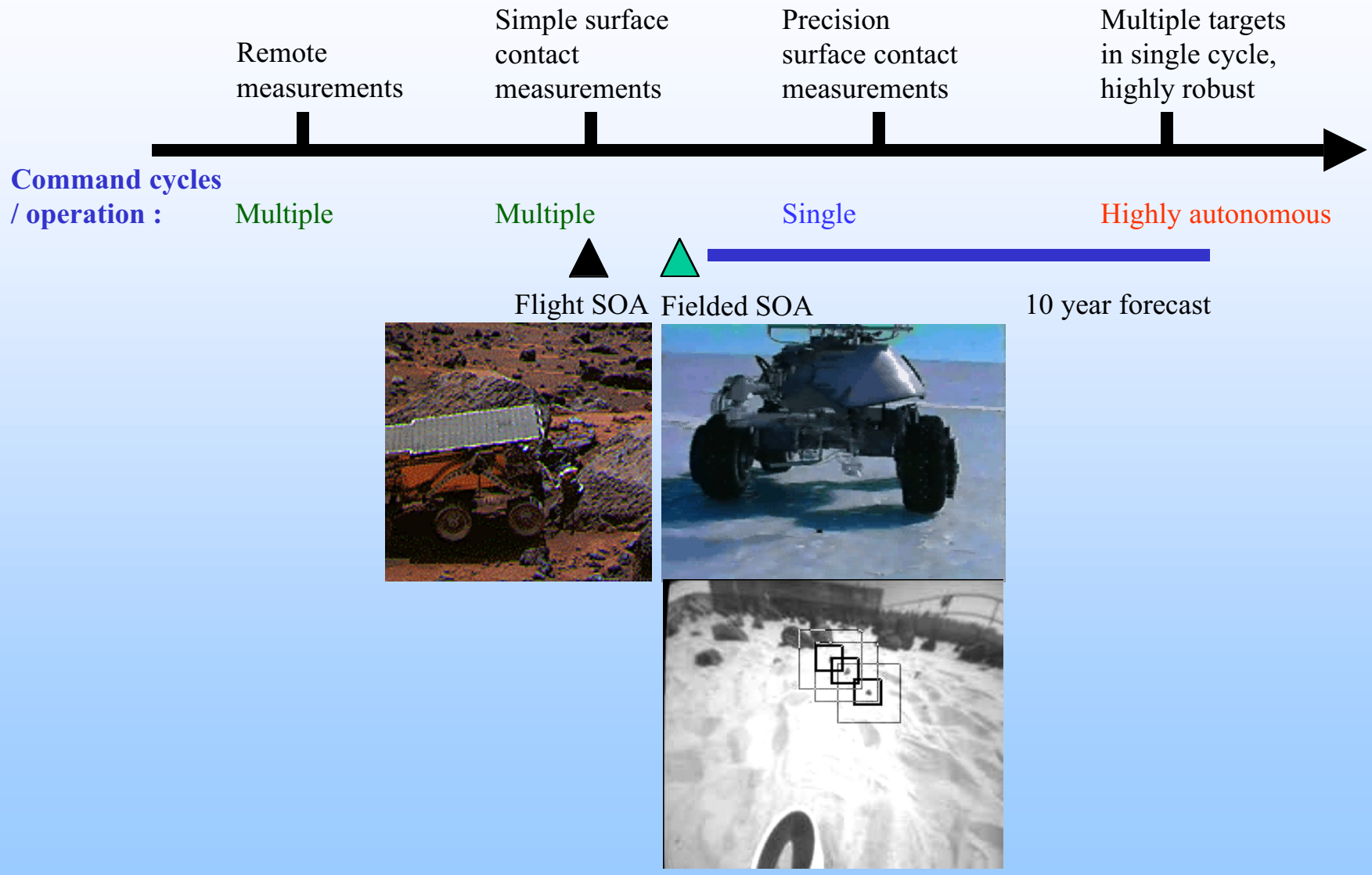
- Visual servoing to target
- Simple contact measurements

Intense Effort:

- Robust visual servoing combined with SLAM to visit multiple targets in a single command cycle.
- Precise contact measurements and autonomous sample manipulation
- Drilling to 1000m depth (Mars conditions)

Breakthrough:

Sample Approach and Instrument Placement



Surface Instrument Deployment Relevant Systems

Nomad 2000

Autonomous approach and placement.

Simple environment.

Limited robustness.

Sojourner

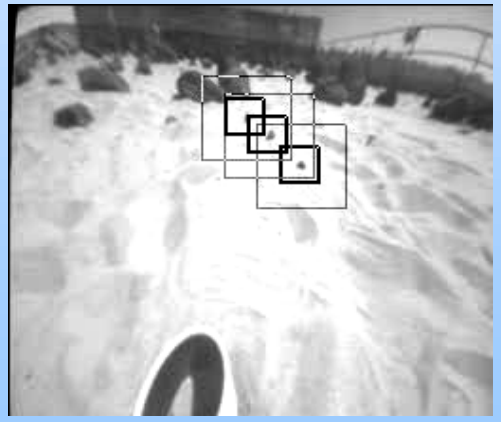
Supervised teleoperation (3-5 command cycles)

Simple contact measurements

Compliant mechanism

Rudimentary “Find rock” capability (unused)

Rocky 7



Visual target tracking

- simple environment
- no occlusions or loss of target

Other Systems

- FIDO (2001) – autonomous target approach using precise visual navigation
- K9 (2002) – work in progre

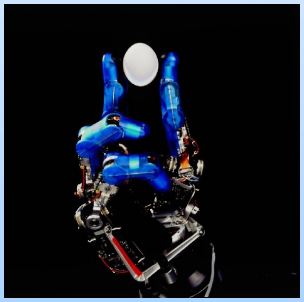
Whole Sample Manipulation

	Imprecise and unpredictable manipulation	Precise and predictable manipulation	Manipulate complex shapes	Operate in complex environment w/ clutter, constraints and occlusions
Command cycles / operation :	Multiple	Multiple	Single	Highly autonomous
Example manipulators:	Scoops, clamshell	Gripper	Dexterous gripper	Human hand

Flight SOA

10 year forecast

Breakthrough



Surface Sample Manipulation Relevant Systems

Robonaut

Tele-operated humanoid robot

Human tool use

Visual feedback only

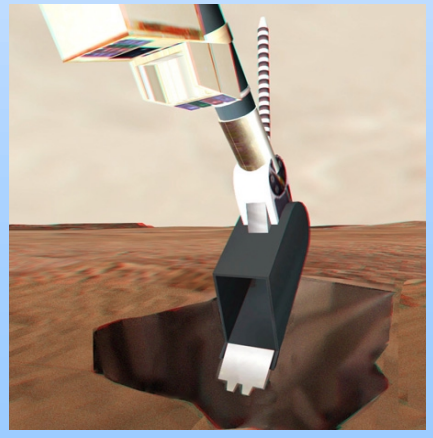
Viking

Scoop to pick up soil, and small loose rocks.

Supervised tele-operation

Imprecise and unpredictable

Mars Polar Lander



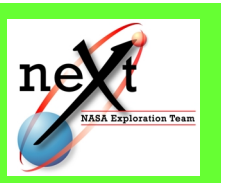
Supervised tele-operation

Imprecise and unpredictable

Deliberately limited to avoid tipping over lander

Other Systems

- Autonomous excavators (CMU)
- Sub-surface vehicles (tele-operated)



Surface Science Perception, Planning and Execution

Surface Science Perception, Planning and Execution

Solved (or will be soon):

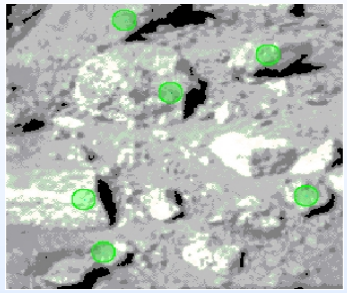
- Ground tools for scientists to plan days events.
- Virtual presence for scientific exploration
- Generation and robust execution of plans with
  - Contingencies
  - Flexible times
  - Weakly interacting concurrent activities

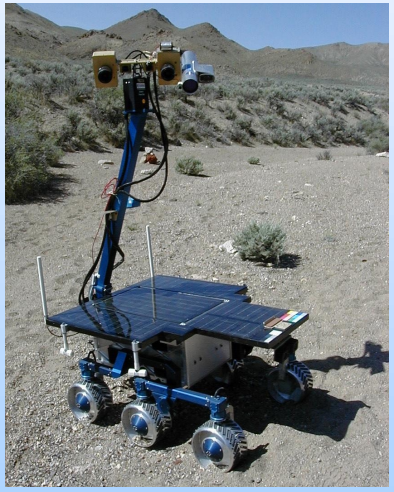
Intense Effort:

- Limited high level science goal commanding for specialized tasks

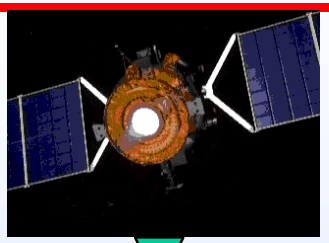
Breakthrough:

- Human level cognition and perception of science opportunities.





Onboard Science Perception and Science Plan Execution



Execution:

None (tele-operation)

Time stamped sequence

Flexible time, contingencies

Prioritized task list with constraints

10 years

High level science goals

Return all data

Return selected data

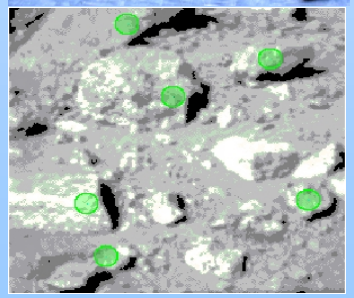
Select targets

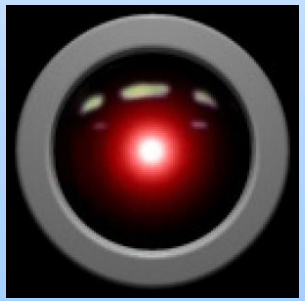
Characterize site

10 years

Recognize unforeseen scientific opportunities

Breakthrough





Perception:

Science Perception, Planning & Execution Relevant Systems

Nomad 2000

Autonomous meteorite identification

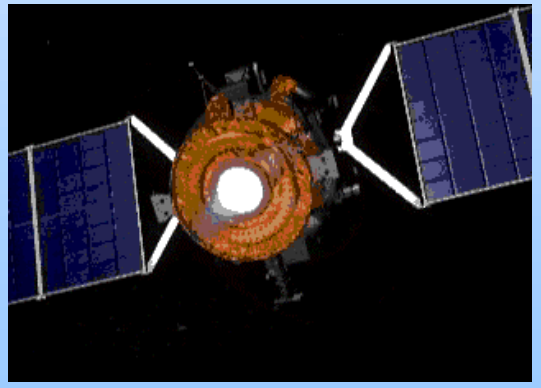
Selects targets

VIZ

Virtual environment for scientific visualization

Ground planning tool for scientists

DS1 / Remote Agent



Onboard planning, scheduling and execution of space-craft operations

Multiple goals; constraints between them, flexible duration.

Other Systems

- MER 2003 + WITS
- GSOM software tools
- APGEN
- K9 Conditional Executive
- FIDO CASPER planner
- And more…

Concluding Thoughts

Concluding Thoughts

- System Design
- Robustness
- Human-Robot Interaction
- Mission Level Objectives
- Technical Challenges

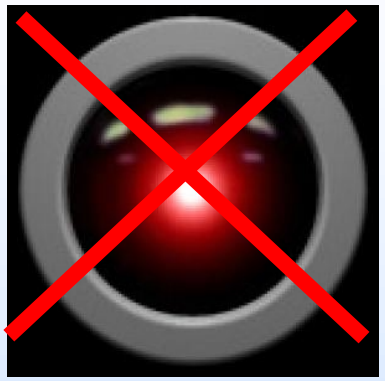
System Design: Specialized vs. General Purpose

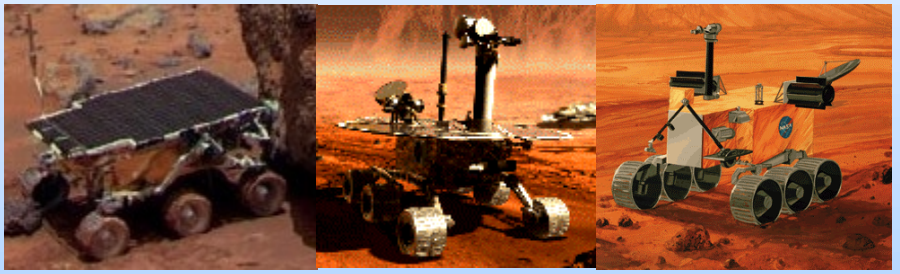
Building general purpose systems is a significant challenge

E.g. can access most terrain types with specialized SYSTEMS (robots and supporting infrastructure).

Challenge of Robustness

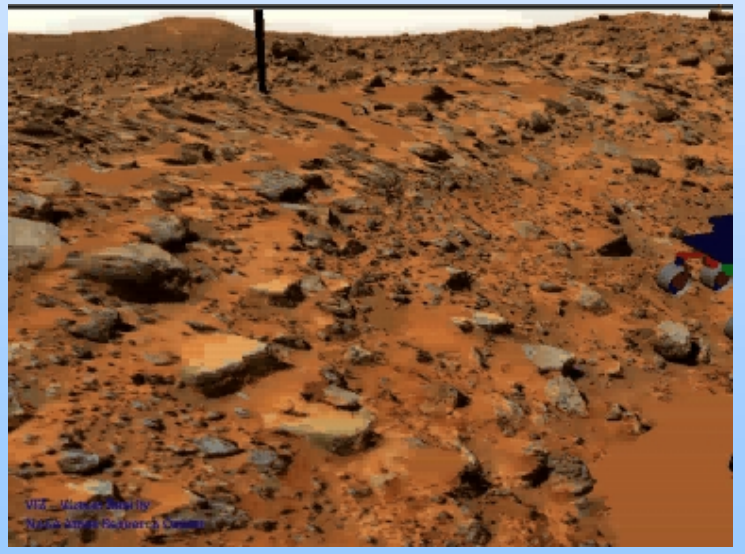
- Human level adaptability and response to adversity NOT likely in near future.
- Achieved through good system engineering:
  - Humans in the loop
  - Specialized machines for each task
  - Sustained testing
  - **Diversify technology base**
- Respond gracefully to unexpected situations:
  - Unmodeled situations ➔beyond orthodox FDIR
  - Adaptation

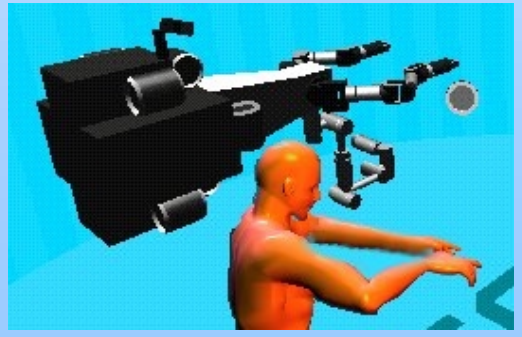




Human-Robot Interaction Challenges

- Establishing a virtual presence
  - Non-visual feedback such as haptic and proprio-receptive.
  - Shared control (low-level control is automated)
- Adjustable autonomy
  - Teleoperation → high-level goal input
- Human-robot teaming
- Human operator to robot ratio
- Interface to non-humanoid robots





Human Control is Not Safe!

- This situation occurred when humans, overriding the autonomous navigation system, went into a very rocky area.
- "Blind" moves and turns were used, compounded by noise on rate gyro.

[Brian Wilcox, JPL]

Mission Level Objectives

Problem

- Scientific perception and discovery
  - "go there and look for anorthosite".
- Construction
  - "Assemble that strut"

Challenges

- Understanding operator intentions (e.g. what strut)
- Planning in open world and using common sense reasoning
- Complex plan execution in uncertain environment

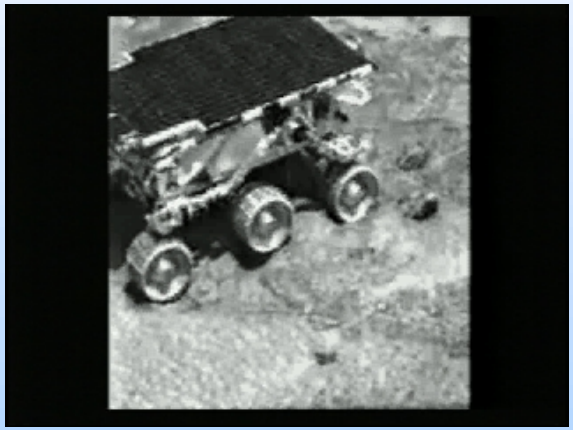
Technology Challenges

- Perception and computer vision
- Robot health monitoring
- Planning, replanning and adaptation
- Non-visual feedback to human operator (e.g., haptic, kinematic)
- High DOF systems
  - Actuation
  - Sensing
  - Control
  - Replication of human dexterity

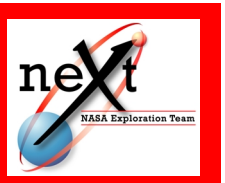
Need for Sustained R&D

- Handful of robots flown

- Significant gap between flight and terrestrial systems
  - Sojourner has more autonomy than was used.
  - MER almost no autonomy



- Massive in place infrastructure for human space flight



Credits

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• Solange	NASA ARC / QSS Group, Inc

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